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Audio- And Subaudio-Frequency Electromagnetic Radiation
At High Latitude

by

ALV EGELAND, SVEN OLSEN and GEORG GUSTAFSSON

Final Report
Task 1 and 2
Contract No. AF 61(052)-600
25 March 1963

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TABLE OF CONTENTS

PURPOSES OF CONTRACT WORK

1. Continued operation of an ELF spectrometer, supplied by the Air Force Cambridge Research Laboratories, for the following main purposes:
   - (a) Investigation of the existence of proton gyro radiation in the auroral zone.
   - (b) Study of the natural background radiation in the frequency range 10 c/s to 10 kc/s
2. Construction of equipment and recording of variations in the earth´s electromagnetic field in the frequency band 1-10 c/s.

ABSTRACT

Fluctuations in the audio- and subaudio-frequency range have been extensively studied in recent years at Kiruna Geophysical Observatory (geomagnetic latitude 65.3°N). At this stage the experimental results can be summarized as follows;

I Band emissions at gyro frequencies of ionospheric ions and hiss frequencies.

Many emission bands, which are quite distinct from the normal back-ground-signals and are obtained as strong enhancements in portions of the spectrum, have been recorded. These observations, with special emphasis on the 700 cps emission band, are reported and discussed. The main results observed for this 700 cps radiation band, are:

(i) The frequency of the maximum signal strength of the emission band is almost constant in time; e.g. at 700 cps $\pm$ 150 cps.

(ii) On the average, the amplitude of the emission at 700 cps is 3 times higher than the normal background noise level at this frequency range.

(iii) The bandwidths of these 700 cps emissions, after taking the equipment characteristics into account, are relatively broad.

(iv) A pronounced morning maximum (between 04 and 10 MET) is found for the different seasons for these 700 cps signals.

(v) The seasonal variation shows that the maximum number of occurrences (of 700 cps emission events) is found for the equinoxes.

(vi) The diurnal variation, as well as the correlation with micropulsations, indicates that the behaviour of the 700 cps enhancements are different from all other frequencies recorded at the Kiruna Observatory.

(vii) It seems likely that the 700 cps radiation is an auroral zone phenomenon.

(viii) A weak Doppler broadening band shift is found for many of the emission events.

The points mentioned above seem to indicate that all these emissions at 700 cps are probably caused by the same physical process or processes. It is considered probable that these emissions consist of

electromagnetic radiation which is propagated in the extraordinary mode along the lines of force of the earth's magnetic field. The hypothesis that the 700 cps signals are generated outside the E-layer, by the arrival of protons, is discussed.

II. Diurnal variation of the background noise between 10 cps to 10.000 cps as a function of frequency and time

(i) There exists almost no diurnal variation in the frequency range between 1 and 3 kc/s.

(ii) Above 3000 cps, the diurnal variation is marked, and it becomes most pronounced for the highest frequencies.

(iii) During the spring and autumn period, the maximum signal strength of the background noise is recorded between 19 and 22 MET, while in the summer months the maximum is obtained 3 to 4 hours earlier. A marked minimum, independent of the seasons, occurs in the morning between 06 and 10 MET.

(iv) The amplitude minimum of the noise is found between 1 and 3 kc/s while maximum signal strength is recorded around 10 kc/s.

III. Cavity modes

(i) Between 5 and 35 cps, the following earth-ionosphere cavity resonances at about 8, 14, 19, 26 and 32 cps, were observed. The first cavity modes at 8 and 14 cps are most pronounced.

(ii) Below 3 cps, spectral lines and band emissions are often observed.

1. Introduction

Investigations of naturally occurring electromagnetic radiation in the audio-frequency range (10 to 10.000 cps) have been carried out at Kiruna Geophysical Observatory (geographic latitude 67.8°N; geomagnetic latitude 65.3°N) since 1958.

The first measurements were carried out at Poikkijärvi, about 7 kms east of the Kiruna Observatory. During three periods of approximately 1 month each (October 12 to November 11, 1958; December 12, 1958, to January 11, 1959; and April 15 to May 14, 1959), continuous recordings were taken of the electromagnetic energy in this frequency range, and the results of these recordings are described and discussed by Gustafsson et al. (1960).

In November, 1961, new measurements in the same frequency-range, but with a somewhat modified, extremely low frequency spectrum - analyser (cf. Section 2), were started. Since then, all our ELF recordings have been carried out near Paksuniemi, about 25 kms east of Kiruna Geophysical Observatory, at a place which is almost free from man-made contamination. The nearest 50 cps power-lines are more than 7 kms from the observation site. Spectro-grams of the electromagnetic energy in the frequency-region between 10 cps and 10 kc/s have been monitored continuously from November 14, 1961, to January 29, 1962; March 10 to April 15; June 5 to July 31; September 15 to December 20, 1962. Furthermore, the measurements have also been extended during the last recording period to include recordings of the background noise in the range 2-40 cps.

The ELF data obtained from the first period of measurement at Paksuniemi are discussed in the Final Report, Task 3, from Kiruna Geophysical Observatory (cf. Egeland et al. 1962) while some of the recordings from the spring period, 1962, are reported by Gustafsson et al. (1962).

The main purpose of this investigation has been to study broad-band noise emissions in the audio-frequency range, in the summer and autumn period, 1962, and compare the results with earlier data recorded in the Kiruna area. Secondly, the diurnal variation has been investigated as a function of time and frequency.

In the following section, a description of the receiving equipment and the method of measurement are given. Furthermore, the antennas used and the frequency- and amplitude-calibrations are also discussed. Finally, the observations and the results obtained, together with a study of correlation with other geophysical phenomena, are reported and discussed in Sections 3, 4 and 5.

Geomangetic fluctuations between DC and 40 cps have been studied by several investigators in recent years (cf. e. g. Aarons and Henissart, 1953; Schumann and König, 1954; König, 1959; Balzer and Wagner, 1960). The noise spectrum has been shown to contain several marked peaks between 6 and 35 cps. The "cavity mode" of radio propagation is discussed in Section 6, while the equipment used for these recordings is described in Section 2.

2. Instrumentation

Two pieces of extremely-low-frequency spectrum analyzer equipments have been used for the measurements discussed in this report. The main part of the data are obtained with the Analyzer described in detail in the Final Report, 7 March 1962, AF 61(514)-1314 (cf. Egeland et al. 1962). This equipment operates in the frequency range 10 cps - 10.000 cps, divided into two bands, 10-1000 cps and 1000-10.000 cps.

(In practice this is not true because the lower range is of little use up to more than 500 c/s. On the other hand good data down to 500 cps is obtainable from the higher band. (cf. Egeland et al. 1962).

The two dominating problems concerned with the measurements, which also apply to the new equipment described later in this chapter, have been:

1. Temperature-control of the equipment
2. Antennas and their matching to the instruments

The temperature control is very important because the sensitivity of the equipment is temperature-dependent. A relatively good solution of the problem was achieved by putting the instrument in a battery-heated thermostat-controlled box made from polystyrene. The whole box of equipment is also placed in the new observing hut at Paksuniemi, where the temperature of the room is controlled by a thermostatic oil pan.

A 12 m high whip and a 10-turn-loop, with a diameter of 32 m, have been used as antennas. It should be noted, however, that the whip has been used very little because of its low sensitivity and difficulties to match it to the analyzer input. Almost all data have therefore been obtained with the loop, which was matched to the input by a microphone transformer 200 Ω/50 k. As the impedance of the loop is frequency-dependent, a good match cannot be ontained over the whole range, but according to the impedance-measurements made, the best match is at about 1 kc/s.

The most important characteristics of the system are listed in Table I. (For further details cf. Egeland et al. 1962).

Table I

	Frequency range	
Maximum gain with 1 µV input at 20°C	10-1.000 cps 1.000-10.000 cps	120 db 123 db
Time of 1 sweep		44 min
Bandwidth	10-1.000 cps	2 cps
Bandwidth	1.000-10.000 cps	40 cps

In order to obtain better accuracy of the recordings in the frequency range 10-40 cps, and at the same time extend the measurement to frequencies lower than 10 cps, a new instrument was constructed and built at the Observatory.

A block diagram of the instrument is shown in Fig. 1. Beginning from the antenna end, it can be seen that, even in this case, at 10-turn circular loop is used. The circumference of this is 300 meters and it also placed horizontally on the ground. The loop is fed direct to the input of the preamplifier, which is a rather much modified version of the preamplifier in the Analyzer mentioned above. It has a minimum voltage gain of about 10^3 and the 3 dB bandwidth is approximately 2-20 cps. From the preamplifier, the signal is fed to the first mixer, where the signal amplitude modulates a 900 cps carrier signal from a Twin-T oscillator. After the mixer follow a number of amplifier stages and then another mixer. Here the 900 cps amplitude-modulated signal is mixed with a signal from a Wien Bridge oscillator

sweeping from about 2350 to 2450 cps. The output of the second mixer, which is passed through a 1500 cps tuning fork filter with 0.5 cps bandwidth, is then amplified and detected and fed direct to an Esterline Angus mA-recorder. A potentiometer mounted on the recorder gives the sweep of the Wien Bridge Oscillator. Assuming that there is no signal in to the preamplifier, this means that there is only a 900 cps signal mixed with the signal from the Wien Bridge Oscillator and there will be only one strong peak on the recorder occurring in the middle of the sweep, when the oscillator gives 2400 cps. Signals from the antenna with frequencies from 2 to 50 cps will occur on both sides of that strong zero peak. By this method it doesn't matter too much if one of the oscillators drifts a few cycles. The zero peak will then not occur exactly in the middle of the range, but all frequencies of interest will still occur on one side even if the drift is as high as 50 cps. An original record obtained with this equipment is shown in Fig. 13. Theoretically, it should be possible by this method to record frequencies down to DC. In practice, however, it is found that the 900 cps carrier must be much stronger than the signals from the antenna in order to obtain good sensitivity. That makes the zero-peak quite broad and in this case it was found impossible to read frequencies lower than about 2 cps.

Although a good deal of data has been obtained with the equipment, there are a few things which should be changed as soon as possible, in order to improve the characteristics of the instrument. One of the most important is to get the frequency response flat over the desired passband. Now there is a strong maximum around 10 cps.

In addition, with this instrument the problems with temperature control and antennas dominate. Temperature control has been obtained in the same way as for the Extremely-Low-Frequency Analyzer; namely with a battery-heated box. Very little has, however, been done until now on the antenna matching, which in this case is even more difficult because of the fact that it is impossible to use transformers at these very low frequencies. Some of the characteristics for the new equipment are given in Table II.

Table II

Frequency range	2-50 cps
Total gain at 20°C	104 db
Bandwidth	0.5 cps
Time of 1 sweep	30 min

3. Variation of the Background Noise between 10 cps and 10 kc/s as a Function of Frequency and Time

Spectrograms of the electromagnetic energy in the frequency region between 10 cps and 10 kc/s have been monitored during the different seasons in 1962 (cf. Section I). The signal characteristics have shown a high degree of variability. Two different pick-up antennas (a loop, and a vertical antenna) have been used in this study, but all data presented in this report was collected with the horizontal loop.

Two normal examples of registrations can be seen in Figs. 2a and b. As is evident from these figures as well as the other original records (cf. also Figs. 6 and 11), the signal strength can vary between relatively wide limits. The minimum detectable noise voltage for the whole frequency range is about 0.1 µV, while maximum measurable intensity is found to be approximately 15 µV. The most normal signal-strengths lie between 0.5 and 3 µV (cf. Egeland et al. 1962).

The diurnal variation of the background-noise in the two bands (10 to 1000 c/s and 1-10 kc/s) has been investigated. For this analysis, the average signal level at 40, 70, 120, 200, 300, 400, 500, 600, 700, 800, 900 and 1000 c/s, as well as at 1, 2, 3, 4, 6, 8 and 10 kc/s, for each sweep, has been scaled. Average amplitude level has been used because it is believed that it gives a good description of the background-noise (cf. Section 6, Hiss).

For the reduction of the spectrograms, the field strength, as recorded with the Esterline-Angus pen recorder, has been plotted on a data-sheet. The amplitude and frequency calibration-curves of the nearest date in the regular calibration scheme have then been used to obtain relative values (in µV) of the background signal-strength, after correction for eventual temperature variation. The µV data are referred to a temperature of 20°C and only days with a temperature variation of less than ± 2° in the equipment box are used.

a) Signal strength variation in the range 1 to 10 kc/s as a function of time and frequency

Figures 3a, 3b and 4 show the diurnal variation of the signal strength in the higher-frequency range for the spring, summer and autumn period, 1962. These histograms are obtained by averaging the data for each period. The results of this study can be summarized as follows:

1. There exists almost no diurnal variation in the frequency range 1 and 3 kc/s. (The 750 cps emissions are not included in this data. Cf. next section.)
2. Above 3000 cps the diurnal variation is marked, and it becomes most pronounced for highest frequencies (cf. Figs. 3 and 4).
3. During the spring and autumn period, the maximum signal strength of the background is recorded between 18 and 22 MET, while in the summer months the maximum is recorded 3 to 4 hours earlier; i.e. between 14 and 18 local time. The time of minimum signal strength in this frequency range varies also somewhat with seasons, but it is always obtained in the morning period between 06 and 10 MET.

Very few other data concerning the diurnal variation in this frequency range are available, so direct comparison is not possible. But the rather great amount of statistical data used (more than 30 days in every period), as well as the similarity between the spring and autumn histograms, seems to indicate that the results are significant. The variation in signal strength as a function of frequency for the summer and equanoctial periods ~~is~~ demonstrated in Fig. 4. A marked minimum of the background noise is found between 1 and 3 kc/s, while the highest signal strength is found at the upper limit of the frequency band. It is probably true that the loop antenna is not perfectly matched over the whole frequency range, so comparison of the signal strength for different frequencies is uncertain. But around 1 to 3 kc/s, the impedance match is better than anywhere else in this frequency band (cf. Section 2).

It is also of interest to compare our results with those of Watt and Maxwell (1957). The latter measurements show a sharp dip in the spectrum near 3 to 4 kc/s and a maximum in the neighbourhood of

10 kc/s, in good agreement with the waveguide propagation model of Wait (1957a and b). Our minimum in the background noise lies between 1 and 3 kc/s in agreement with data from Heirtzler et al. 1960, while the maximum also occurs at 10 kc/s or even heigher at Kiruna. More data must be obtained before it is possible to draw definite conclusions about the seasonal variation of the low-frequency background noise, but some preliminary results can be found from the data analyzed. Maximum signal strength is observed in the summer period. In the spring and autumn period, 1962, the background noise varies very little; but the average signal level is markedly below that recorded for the summer period.

b) Variation of the signal strength in the frequency range 10 to 1000 c/s as a function of time and frequency

The diurnal variation for the spring and summer period, 1962, is shown in Figs. 5a and b. The variation in the signal strength between 10 and 1000 cps is rather small, but a marked minimum in the morning (between 06 and 10 Local Time) is found for the frequency range 10 to 500 cps (cf. Figs. 5a and b). On the other hand, the background noise between 500 and 1000 c/s shows a weak maximum at this time. Furthermore, these figures, indicate that signal strength of the naturally occurring noise is highest between 70 and 250 cps and the intensity of the fluctuations decreases very rapidly from 120 cps to about 500 cps. Above 500 cps, the signal strength decreases very slowly. (cf. Figs. 5a and b).

The variation in signal strength as a function of frequency is in rather close agreement with the results reported by Heirtzler et al. (1960) and Wilcox and Maple (1957), except for the frequency range 500 to 1000 cps. The strong emission in this frequency range at Kiruna (cf. Section 5) may be the reason for this difference.

4. Broad Band Noise Emissions at 700 cps

That the noise emissions in the audio-frequency range may exhibit one, or sometimes two, peaks in the spectrum, has been observed earlier in the auroral zone by Egeland (1959), Aarons et al. (1960), Egeland et al. (1962) and Gustafsson et al. (1962). The noise peaks in most cases have been near 700 cps and between 2 and 3.5 kc/s. It has been suggested that the peak near 700 cps, which has been

rather stable in frequency, might be due to gyro-radiation from protons of moderate to low velocity. (This hypothesis will be discussed further in Section 6.) Some original examples of such peaks are shown in Fig. 6. The gyro-resonance frequency of protons is 755 cps at an altitude of 100 km, for a total magnetic field of 0.53 Gauss, which is the average value of the field in the Kiruna area.

In the following, different experimental observations of 700 cps peaks are discussed.

a) Occurrence and duration

During a 20-day period in March and April, at Kiruna, 22 per cent of all frequency sweeps contained 700 cps radiation with an amplitude well above the quiet level (cf. Gustafsson et al. 1962). During a 3-hour interval, centered at 0900, the contribution was as high as 46 per cent for the spring period. For the summer period, 9 per cent of all sweeps showed a marked resonance effect around 700 cps, while for the autumn period about 8 per cent of all sweeps contain a marked peak around 700 cps. In the winter period only 2 per cent of all sweeps show a resonance peak at 700 c/s (cf. Fig. 7). This is still far more than has been obtained during earlier recording periods in 1958 and 1959 (cf. Gustafsson et al. 1960). As the sensitivity of the equipment has been almost exactly constant during all ELF measurements at Paksuniemi in 1961 and 1962, the maximum frequency of occurrence during the April-May recording must be due to the fact that the 700 cps emission is more likely to occur during the spring season.

Most of the events of 700 cps radiation lasted for several sweeps and the longest one remained almost steady at an intensity of about one microvolt for twelve sweeps, which means almost nine hours (cf. Point f).

b) Day-to-day variation

The frequency band centered at 700 cps has a different day-to-day variation than the other frequencies in the whole range (cf. Gustafsson et al. 1962). This is probably due to the fact that the band at 700 cps is caused by a different physical process (viz. gyro emission), while the others mainly show the variation of the noise from atmospherics.

c) Diurnal variation

The diurnal variation of the 700 cps emission for the spring, summer and autumn, 1962, as well as the variation of all such emission peaks is shown in Fig. 7. This figure clearly demonstrates that the 700 cps-radiation has a diurnal variation which is different from the background noise of the other audio-frequencies (cf. Figs. 3 to 5). The maximum number of occurrences always appear between 0600 and 1100 local time. A similar pronounced forenoon maximum was not obtained during the earlier recording periods in 1958 and 1959, during which the events seemed to be more randomly distributed in time. However, there were only eleven events and therefore no direct comparison could be made. The number of 700 cps peaks are probably still more pronounced between 09 and 11 MET than Fig. 7 indicates, due to the fact that calibration and other checks of the equipment are made at that time (cf. Fig. 8).

d) Signal strength

The average background radiation at 700 cps, when all emission peaks at this frequency are excluded, is about 0.3 μV at the input of the amplifier and it may vary during a one-month period from a minimum of 0.22 μV to a maximum of 0.4 μV for the daily average. The maximum value of the intensity of the 700 cps band for a few events exceeded 4.0 μV, which means that this radiation is sometimes more than ten times stronger than the background, as measured at 700 cps. The average ratio between the 700 cps emission and quiet conditions at 700 cps is found to be to about 3.

e) Frequency stability and bandwidths of the 700 cps emissions

Usually it has been found that the frequency of the maximum amplitude of the emission band is centered at 700 cps and that it is fairly constant, i.e. varies about $\pm$ 150 cps. For a few events the frequency of the maximum amplitude may vary still more. This is discussed in Point f.

The average half-intensity band-widths of all 700 cps radiation in summer and autumn, 1962 are shown in Fig. 9. Normally the average half-intensity width is $\pm$ 200 cps, but the bands seem to be somewhat broader for strong 700 cps emissions.

f) Fine structure

A few measurements have been made of the 700 cps radiation with the sweep disconnected. An example of this type of record is shown in Fig. 10. It can be seen on the record that an almost sinusoidal type of oscillation occurred between 0940 and 0950, with a frequency of 25 $\pm$ 3 seconds per period. The maximum peak to peak amplitude of the oscillation was 1.8 μV. This corresponds to a field strength of the order of 1 μV/m. These oscillations occurred during a magnetically quiet period, and on the magnetic record there could be seen during the same time-interval, a variation of the X-component with approximately the same period (25 seconds per period) and with an amplitude of about 2 gammas. It can also be seen from Fig. 10 that the intensity of the 700 cps radiation may change rather rapidly with time and this may influence the shape of the emission band markedly when recorded by the slow sweeping technique. Furthermore, the 700 cps radiation events which have lasted for several sweeps (cf. Point a) are not believed to be constant for such a long time, but rapid time variations are surely superimposed. On five sweeps in the autumn period, 1962, the resonance peak at 700 cps is split up into two marked resonance peaks. One example of this effect is shown in Fig. 11. One of the peaks normally has its maximum amplitude around 500-600 cps, while the other maximum is found in the frequency band around 1000 cps. Due to the slow sweeping technique used in our measurements, it is uncertain whether these observed double peaks are physically real, or are only due to very strong variations of the radiation as a function of time (cf. Fig. 10). This effect will be discussed more in Section 6.

The exact shape of the emission pulse is difficult to determine from our recordings because rapid time variation may be superimposed. But from the cases where it has been possible to measure the shape, it seems to be relatively symmetrical although the decrease in signal strength is slower above frequency of maximum amplitude (normally around 700 cps) than below this frequency (cf. Fig. 12a and b).

g) Latitude dependence

From the results reported by Gustafsson et al. (1962), it seems reasonable to conclude that the 700 cps radiation is much more

pronounced at the auroral zone latitudes as compared with lower latitudes. To the authors' knowledge, the 700 cps resonance peak has only been observed within or close to the auroral zone.

h) Correlation with geomagnetic disturbances

It was found at Kiruna, by Aarons et al., (1960), that the 700 cps emission was correlated with micropulsations in the geomagnetic field. The sensitivity of the ELF equipment has been increased since 1960 and the instrument has been placed at a site where the local noise level is lower (Paksuniemi), so it is now possible to detect 700 cps emissions of much smaller amplitude. During the last recording periods it has not always been possible to find any deflection on the magnetograms (which means that they are less than about one gamma) at times when there have been weak 700 cps emissions. The reason for this lack of correlation may be either that the sensitivity of the magnetovariograph is too low, about one gamma, or that a strong disturbance was occurring at the same time, making the reading of very small amplitudes impossible.

5. Hiss

The high-frequency emission band, in the range 1.5 to about 5 kc/s was called hiss by Watt (1957). Marked hiss was recorded for more than 30 sweeps in the winter period 1961 to 1962 (cf. Egeland et al., 1962) and, in three cases, it occurred on two or more consecutive sweeps. The noise peaks in this band are much more variable. Peak frequencies varying from 1.8 to about 5 kc/s occur. One example of hiss recorded at Kiruna can be seen in Fig. 6. On some occasions, broad-band noise has been recorded simultaneously for some sweeps in both the frequency range 500-1000 cps and 1500-5000 cps.

Noise bands have also been observed between 5 and 10 kc/s, but in this band they are less common and the maximum noise-strength is always relatively low. These noise peaks show, in many instances, (cf. e.g. variation in frequency, amplitude and form) a marked similarity to hiss, although contributions from atmospherics and whistlers may be important.

No broad absorption bands have been recorded during the whole observation period.

As seen on all the original records (cf. e. g. Figs. 2 and 6), many strong spikes (spectral "lines") have been recorded, but they have not been analyzed in any detail, as our main aim was to investigate noise bands. A rough estimate of the recordings seems, however, to indicate that the strong spikes are rather irregular both in time and frequency and they have been recorded at almost all frequencies. It is therefore certainly unreasonable to believe that all of them are spectral "lines" due to emission from the exosphere. Some of these strong spikes may arise from local man-made noise such as interference from power-lines, cars, motors and different electrical discharges. The majority of the spikes are probably due to atmospherics, dawn chorus and whistlers or similar phenomena.

6. Cavity resonance

The relatively small amount of available experimental data, concerning the cavity resonance between 5 and 40 cps, has lead to increased activity in this extremely low frequency range during recent years. In 1952, Schumann first discussed mathematically the electromagnetic cavity resonance in a two dimensional wave guide bounded by the earth and the lower ionosphere. A fundamental-resonant frequency equal to about 10.6 cps should be expected for a perfect conductor at the frequencies of interest here, and the problem discussed by Schumann (1952) has later been investigated for different ionospheric models (cf, Wait, 1960; Raemer, 1961 a and b; Galjes, 1961). The first experiments designed to detect the cavity mode in the 8 to 11 c/s range were carried out by Schumann and König, (1954) and König, (1959). More recently new field measurements were carried out by Balser and Wagner (1960 a and b), and since then more experimental papers concerning the cavity resonance have been published (cf. e. g. Gendrin and Stefant, 1962 a and b; Polk, 1962; Polk and Fitchen, 1961).

The agreement between the calculated terrestrial ELF noise-spectrum and the measured spectrum is very good.

The small variation of the resonant frequencies from event to event, and the shift of these frequencies downward from the value which it would have in a perfectly conducting cavity, are believed to be a rather sensitive indication of effective ionospheric conductivity and height.

Furthermore, the frequency widths of these cavity modes give some indication of the average properties of the ionosphere over the region which contributes to propagation.

With the sub-audio spectrometer described in Section 2, measurements of the natural radiation background noise, in the frequency range 2 to 40 cps, have been carried out at Paksuniemi between October 15 and December 20, 1962. During the first part of the recording-period many changes in the equipment were necessary before it operated satisfactorily.

The first preliminary data is presented below. The cavity modes vary considerably with time, and for some periods they may be very strong. Normally the first mode at about 8 cps is most pronounced, and the frequency of maximum amplitude usually occurs at 8 cps within $\pm$ 1 cps. The half intensity frequency-width seldom exceeds more than 1 cps. On a few occasions, the signal strength at the second mode (around 14 cps) is higher than at the first. See Fig. 13 where two examples of original records are demonstrated.(cf. Section 2).

The number and the relative occurrence of resonance frequencies between 6 and 35 cps, recorded in November 1962, are shown in Fig. 14. This figure shows that especially the first mode, but also the second mode, are recorded very often at high latitudes. The higher modes are much less marked, but this may well be due to the much lower sensitivity of the equipment above 16 cps. The curve in Fig. 14 has not been corrected for this characteristic. There also seems to be a marked diurnal variation in the occurrence of these cavity modes, but the data obtained hitherto are too small for any definite conclusion to be drawn on this point.

Another interesting result from this measurement is the considerable number of , narrow frequency bands, with high intensity, below 3 cps. (cf. Fig. 14).

On thirteen occasions in the winter period, very large enhancements of the background-noise were found within the range between 25 and 45 cps, with the maximum intensity at about 32 cps. These recordings were found with the audio-frequency spectrometer, where the sensitivity of the equipment is rather low for frequencies below 20 cps. In one case, this type of signal continued for two sweeps. cf. Egeland

et al 1962). If the radiation comes from sodium within the E-layer, its gyro frequency should be about 32 cps. In one case, the enhanced component of the signal-level at 32 cps was 8.8 μV above the back-ground-noise-level. At 32 cps, this corresponds to a change of $0.9 \cdot 10^{-3} \gamma$ or $2.7 \cdot 10^{2}$ μV/m. Similar low-frequency emission around 32 cps has been discussed earlier by Aarons (1956).

The observed peaks at 32 cps lie, however, at the same frequency as the 5th resonant mode of the earth-ionosphere cavity resonance and it seems not unreasonable that the background noise may be modified by this mode.

7. Summary and Discussion of the 700 cps Radiation

The main observed properties of the 700 cps radiation may be summarized as follows:

a) The frequency of the maximum signal strength of the emission band is almost constant in time; e.g. at 700 cps $\pm$ 150 cps.
b) The amplitude of the emission band centered at 700 cps is for many events five time or more higher than the normal background noise level in this frequency range.
c) The frequency bandwidth of these emissions, after taking the equipment characteristics into account, is normally around 200 cps.
d) A pronounced morning maximum (between 04 and 10 MET) is found for the different seasons.
e) The seasonal variation shows that the maximum number of occurrences (of 700 cps emission events) are found at the equinoxes.
f) The diurnal variation, as well as the correlation with micropulsations, indicates that the behaviour of the 700 cps enhancements is different from the back-ground noise, which has been recorded in the audio-frequency range.
g) It seems likely that the 700 cps radiation is an auroral-zone phenomenon.
h) A weak Doppler broadening and shift is found for many of the 700 cps emission events.

The points mentioned under a) to h) seem to indicate that all these emissions at 700 cps are probably caused by the same physical process or processes.

The ELF equipment has also been in operation during strong Polar Cap Absorption events, when relativistic protons are emitted from the sun. But during these events no resonance effects have been observed between 600 and 1500 cps.

Furthermore, it could be mentioned that Aarons et al. (1960) (cf. also Egeland, 1959) first detected ELF emissions associated with geomagnetic pulsations having periods of the order of 30 sec to a few minutes at Kiruna Geophysical Observatory. Ellis (1960) has also found at Camden (geomag. lat. 42°S), Australia, that bursts of VLF noise coincide with geomagnetic pulsations (of about 1 min).

The different hypotheses proposed for the origins of ELF and VLF emissions are briefly discussed in the following:
One of the first known is the travelling-wave hypothesis (cf. Gallet and Helliwell, 1959; Gallet, 1959), which suggested that, since charges particles and electro-magnetic waves follow the magnetic field lines, some interaction may occur between the two radiations in a manner analogous to that of a travelling-wave amplifier and, as a result, the frequency component having about the same velocity as the particles will undergo amplification. The velocity of the electromagnetic radiation depends on the magnetic field strength and ambient electron density, the position on the field line will determine the frequency to be amplified.

Kimura (1961) concluded that the travelling-wave tube-like amplification of VLF electromagnetic waves by an electron beam in the exosphere, does not cause any amplitude growth of the electromagnetic wave. By the interaction of the electromagnetic wave with a cyclotron mode of a proton beam (amplification due to the transverse interaction of the extraordinary mode) an amplitude gain of 4 db per 100 km for a 3 kc/s wave is expected, provided that the proton beam has the density of 10^7 cm^{-3}. It still remains to show that this theory is applicable to the conditions in the exosphere.

Cerenkov effect has also been suggested as a possible origin of radiation (cf. e. g. Chamberlain, 1961). Cherenkov radiation of a certain frequency takes place if the velocity of a charged particle in a medium exceeds the phase-velocity of the electromagnetic waves of the frequency in the medium. If the particle approaches an observer with velocity U_o,

the observed frequency of the cyclotron radiation will shift upwards due to Doppler effect. The intensity of the Cherenkov radiation possible in the exosphere seems to be too small to account for the observed maximum strength of the emission.

Allcock (1957) has suggested that ELF emissions might be attributable to plasma oscillations in the exosphere (cf. also Emeleus, 1951). Unfortunately, since very little is known about such oscillations (Spitzer, 1956), this conjecture is higher speculative.

Poeverlein (1961) has discussed the case when noise radiation of about one kc/s is emitted in the higher atmosphere, part of it (an extraordinary wave) is propagated downward into the space between the earth and ionosphere. Reflection at the earth and ionosphere leads to a standing wave in this space, having a power flux whose intensity varies much with frequency. (Max. field strength is derived for the resonant frequencies of the space.)

The space between earth and ionosphere is comparable to an air gap between two parallel plane reflectors. Resonance is observed when half a wavelength or multiples of a half-wavelength fit into the space. The lower ionosphere is, however, only a partial reflector, allowing radiation to enter the resonance space and causing at the same time some loss of energy out of the resonance space (leakage). Poeverlein considered reflections from either the E- or e D-layer and he found resonance peaks in the range between 400 and 3000 cps.

Gintsburg (1961) has considered the cyclotron radiation from the solar corpuscular streams. When taking into account the superlight character of the motion, he found that the ions radiate also at frequencies less than the gyromagnetic frequency of the plasma ions. He obtained three emission bands, one in the micropulsation region and two in the ELF region, in agreement with our measurements.

In the following we shall discuss the hypothesis of proton-cyclotron radiation mentioned above (cf. also Mac-Arthur, 1959) in more detail. The fact that the 700 cps emissions correlate relatively well with the magnetic activity, but not with the diurnal of

terrestrial phenomena such as lightning, (cf. the diurnal variation curve of world-wide thunderstorm acitivity in Handbook of Geophysics, 1960) seems to indicate that the origin of this 700 cps

emission exists in the exosphere rather than in the space below the ionosphere.

Santirocco (1960) attempted to compute the power expected from such a process and concluded that it seems so weak that it should not be detected on the ground. However, he had to make a number of questionable assumptions, and therefore his calculation is probably not sufficient basis for rejection of the proton-gyrofrequency hypothesis. Of the possible radiation which could originate from this motion of protons, only the proton-cyclotron frequency in the extraordinary polarization is likely to be detected on the ground. For this whistler mode the index of refraction is very much greater than 1, so the Doppler shift is relatively large. From the fact that no 700 cps emission was recorded during PCA events, it seems reasonable to conclude that the electromagnetic radiation, centered around 700 cps, should be due to protons of moderate to low velocity, such as those associated with the proton-aurora (cf. also Marcray and Pope, 1960). The Doppler shift of the protons during PCA should be very large, and therefore no emission band between 500 and 1500 cps is observed during these events.

Also the auroral spectra show that both H_{α} (6563Å) and H_{β} (4861Å) lines are Doppler shifted. According to Omholt (1962), the main part of the protons, which arrive almost parallel to the earth's magnetic field lines, have energies between 1 and 100 kV, and the energy distribution function varies approximately as E^{-2}. The Doppler shift emitted corresponds to velocities of the order of 10^2 to $2 \cdot 10^3$ km/sec. The average velocity should be about $5 \cdot 10^2$ km/sec, but considerably higher velocities have also been reported in the literature.

Murcray and Pope (1960) have made some semiquantitative treatments of this mechanism to calculate the shape of the frequency-vs-time curve which would be produced by incoming protons of a given velocity. The authors have to assume the free electron distribution in the outer ionosphere and exosphere. From their results it seems quite clear that protons with a relatively moderate velocity will suffer a marked Doppler shift.

As several properties concerning the protons (as e.g. density and velocity distribution, as well as ionospheric irregularities) and the magnetic field above 100 kms are not too well-known, no rigorous theoretical examination of the emission from protons, has been carried

out. It is therefore difficult to estimate the exact signal characteristics on the ground from such emission.

In the paper by Aarons et al. (1960), we proposed that the 700 cps radiations were generated at about 100 km above the earth's surface. Later on, when more data had become available (concerning frequency of maximum amplitude,fine structure of frequency band as well as its diurnal variation), it is believed that the 700 cps signals may often be generated at a higher altitude by the arrival of protons. The resonance frequency emitted by the protons will vary as it approaches the earth's surface, because the cyclotron frequency will change with changing magnetic field. The Doppler shift for a particular frequency will also change because of changes in the index of refraction for propagation along the magnetic field in the extra-ordinary mode (cf. e.g. Ratcliffe, 1960; We are only interested in frequencies much less than the gyro-frequency of electrons.)

The picture is surely more complicated than that presented above. The influence of the protons on the index of refraction has not been considered either.

Future Plans

The investigation of audio-frequency background-noise described in this report shows, in many instances (cf. e.g. the presence of so many examples of low-frequency emission bands during the short period of recordings, the change in diurnal variation with frequency, etc.), the difference between it and similar measurements at lower latitudes. And this study further indicates the prevalence of spectral bands in the auroral zone.

Additional measurements, and an extension of the present recording program to increase the time resolution of the recordings below 3 cps, are being planned. A special study will be made of both the vertical- and horizontal-component of the background radiation, using both a vertical and a horizontal loop. On the technical side, a new broad-band amplifier, similar to the one described in Section 2 but without any frequency sweep, has been built. The background noise in the range 10-10.000 cps is now recorded simultaneously for some periods, both with the recording method used here, and with the new amplifier using a magnetic-tape-recorder. This will obviously be of help for a better

understanding of the background noise. Correlation studies with other geophysical phenomena will be carried out.

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Low frequency (2 to 40 cps) spectrum analyser

Block diagram

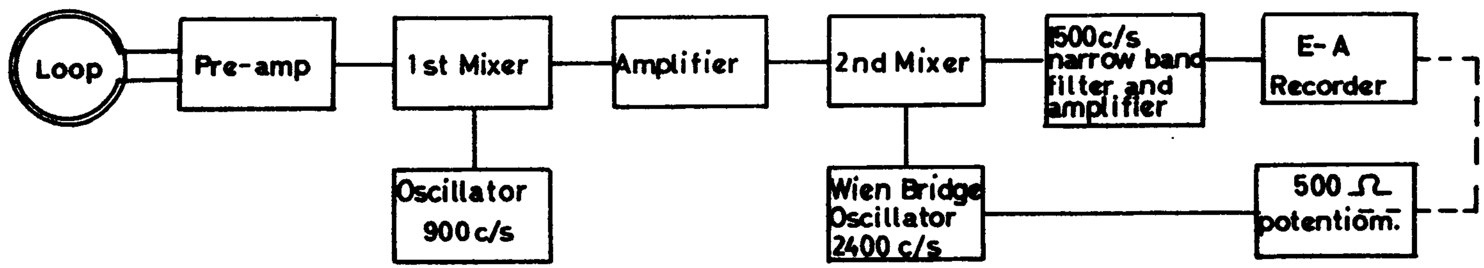


Fig. 1

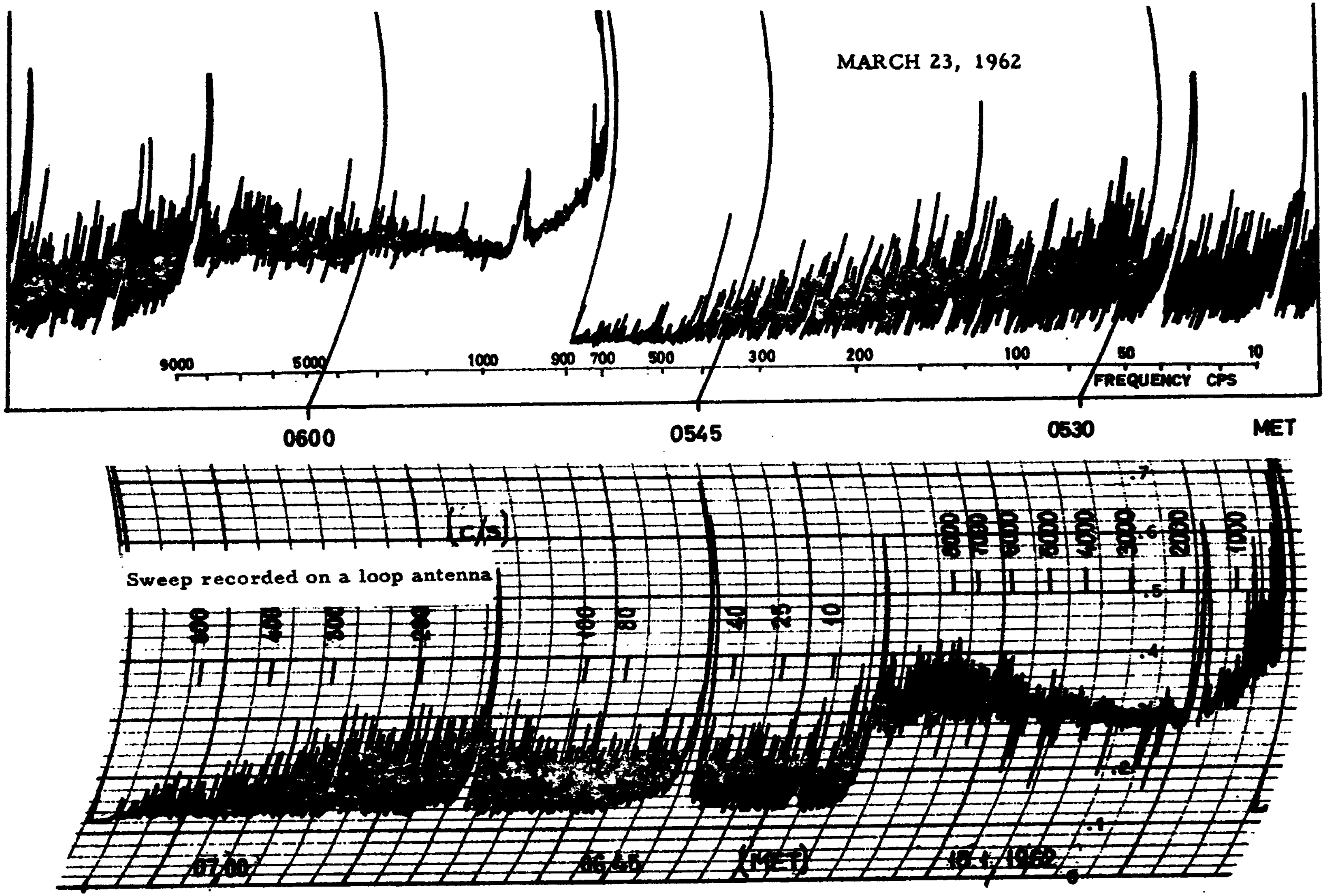


Fig. 2. Two normal frequency sweeps recorded at Paksuniemi

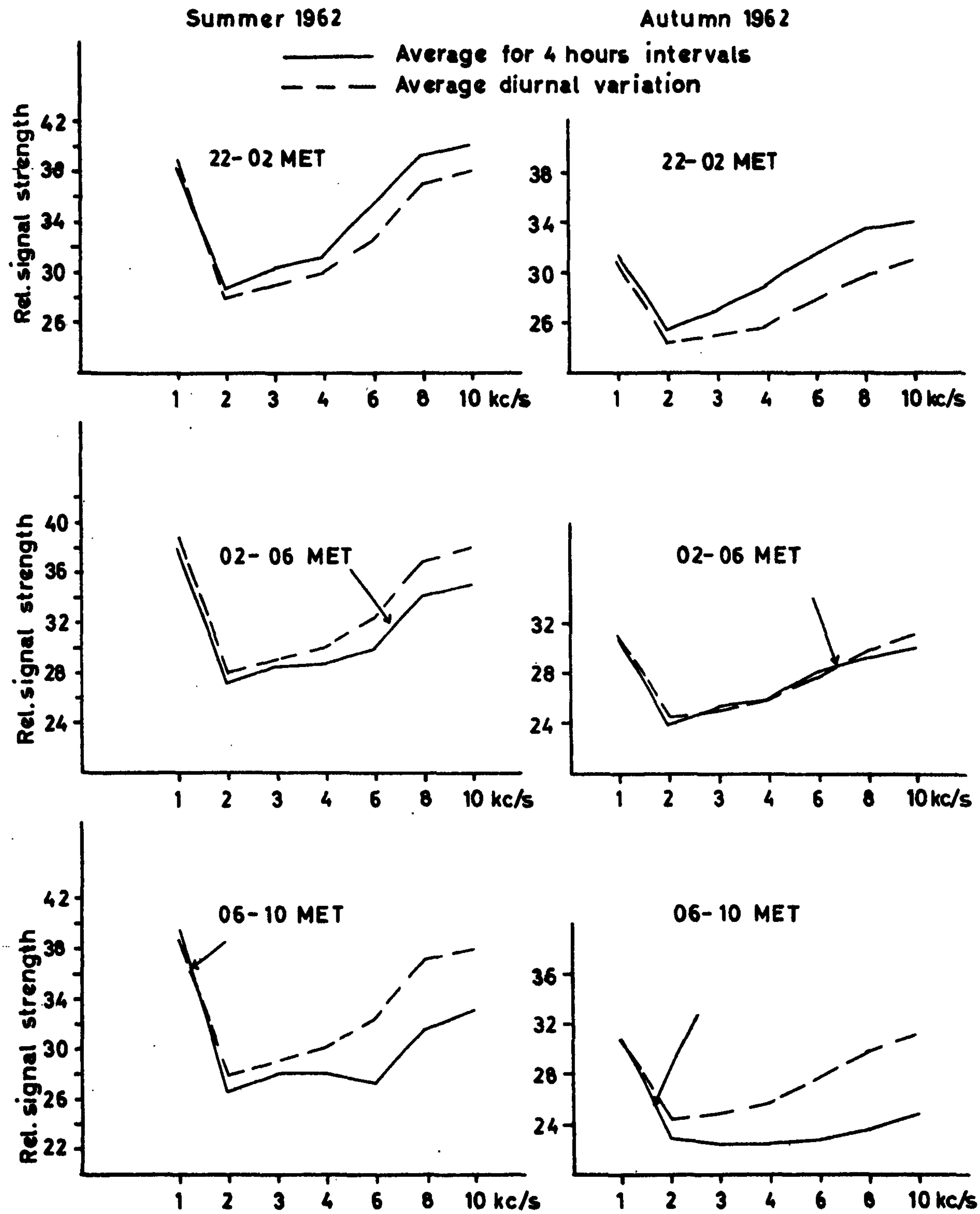


Fig. 3 a.

Average variation of the background noise in the frequency range 1-10 kc/s during the summer and autumn period, 1962.

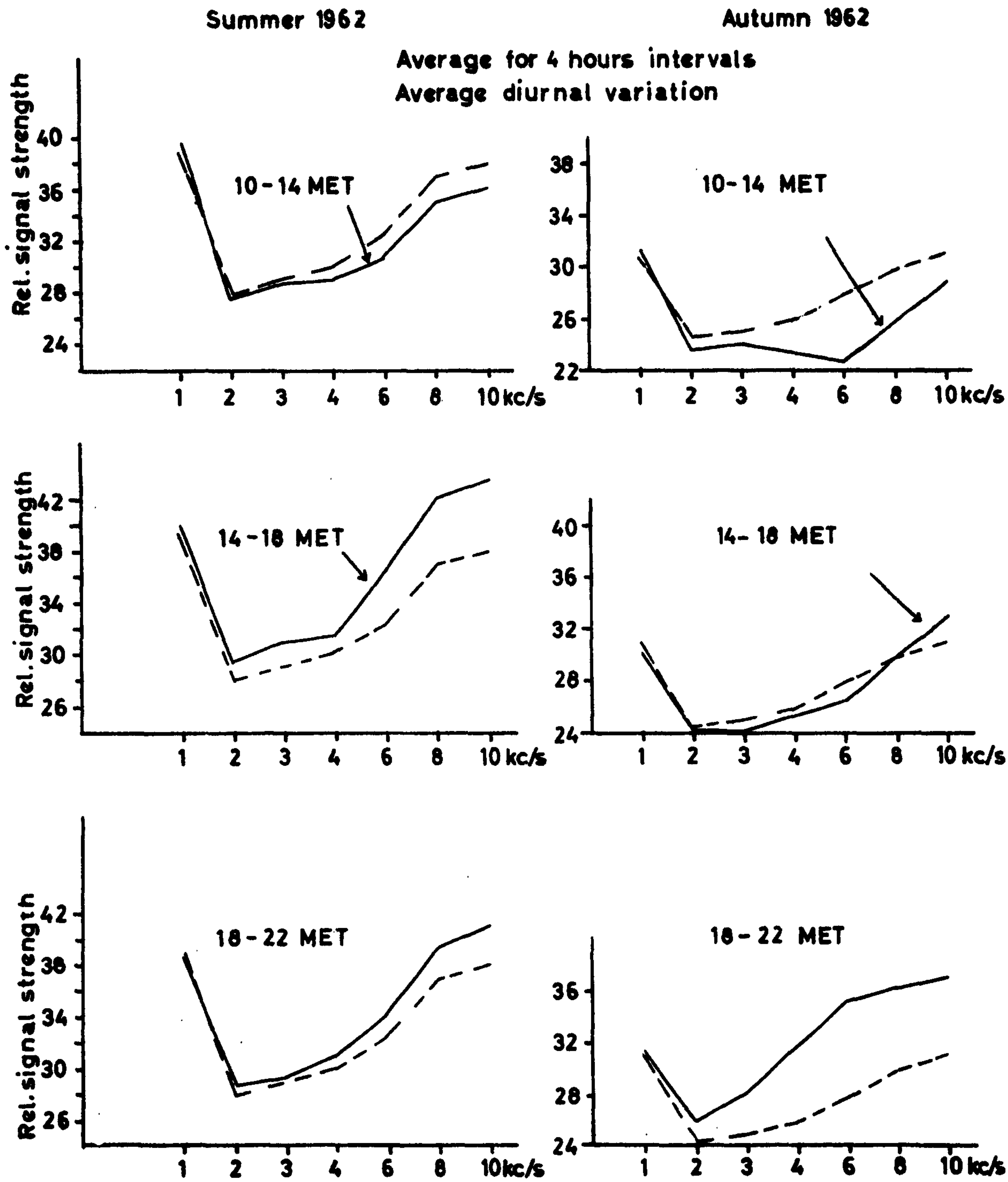


Fig. 3 b.

Average variation of the background noise in the frequency range 1-10 kc/s during the summer and autumn period, 1962.

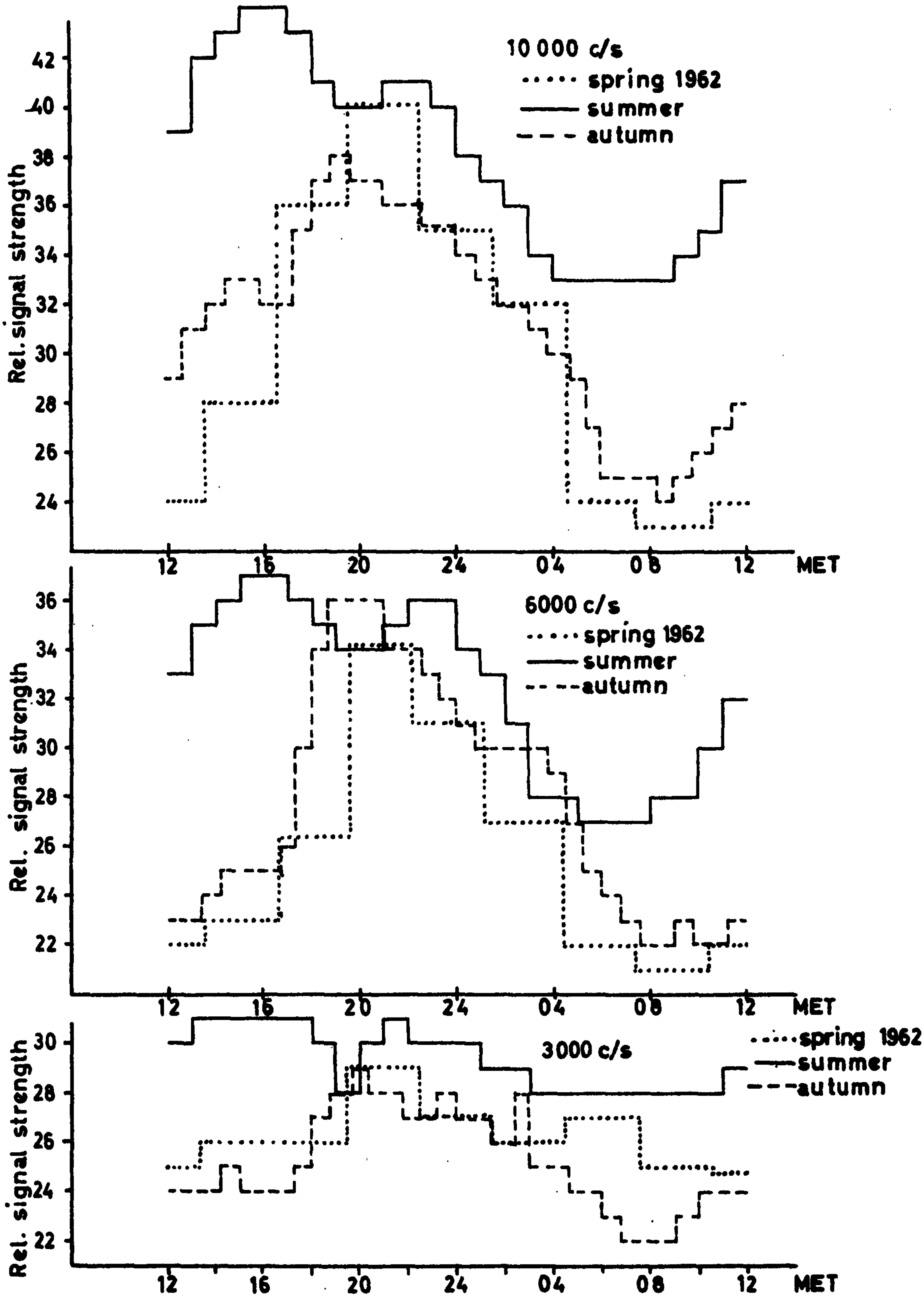


Fig. 4. The average diurnal variation of the background noise at 3000, 6000 and 10.000 c/s for the spring, summer and autumn, 1962.

Fig. 5 a. Variation in the background noise between 40 and 1000 c/s as a function of time of day for the spring period, 1962

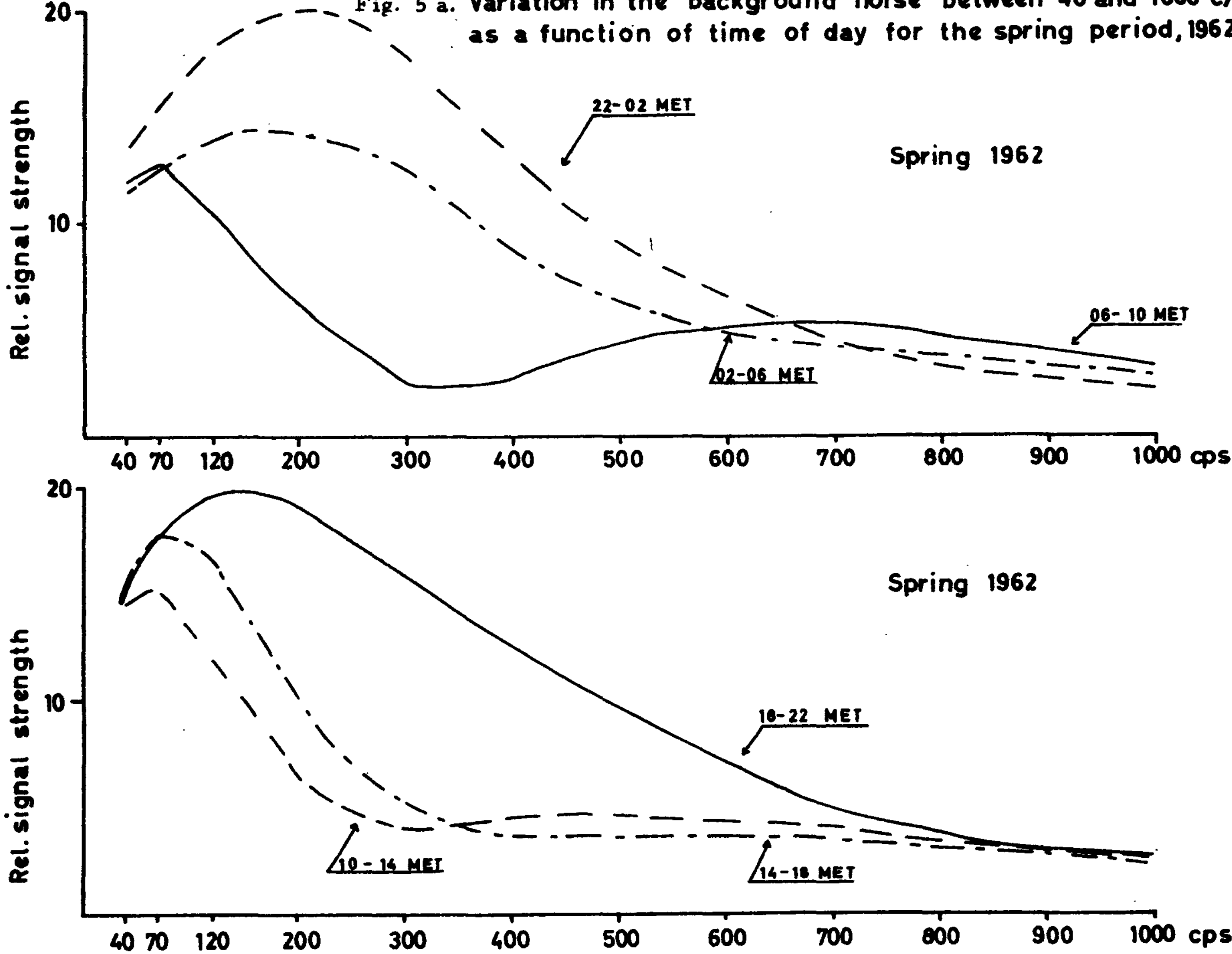
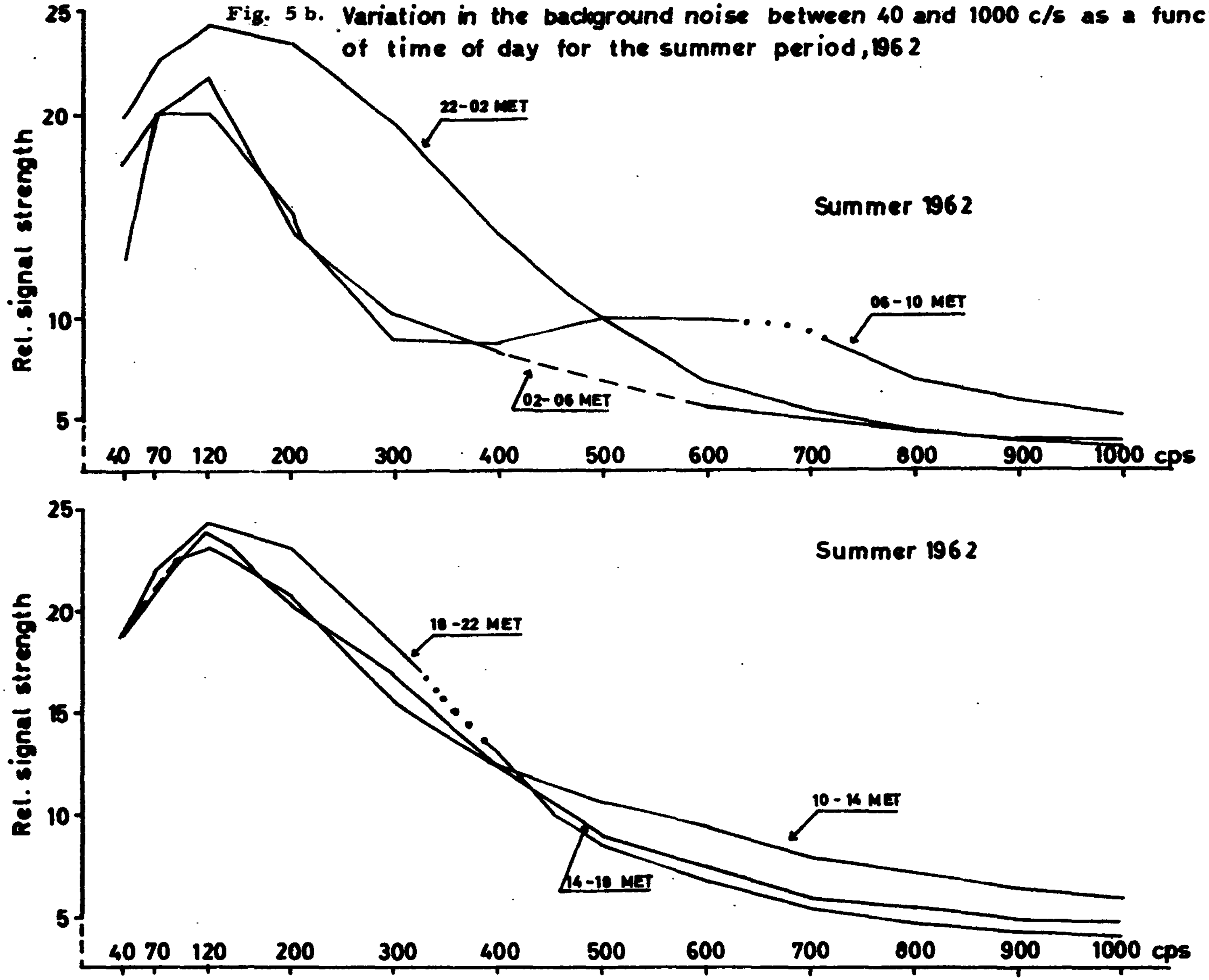


Fig. 5 b. Variation in the background noise between 40 and 1000 c/s as a function of time of day for the summer period, 1962



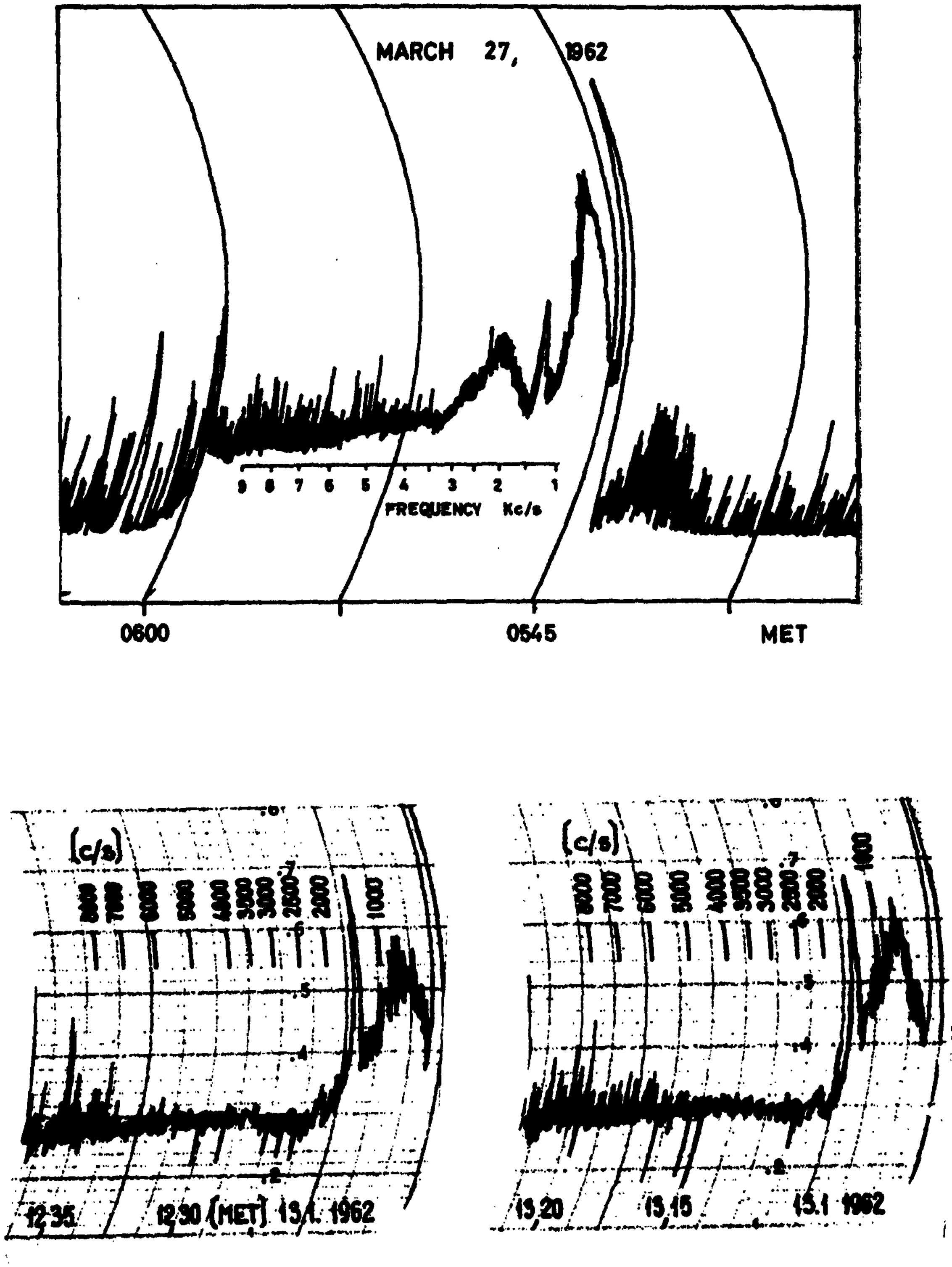


Fig. 6.

Example of sweeps showing 750-radiation and hiss (Paksuniemi)

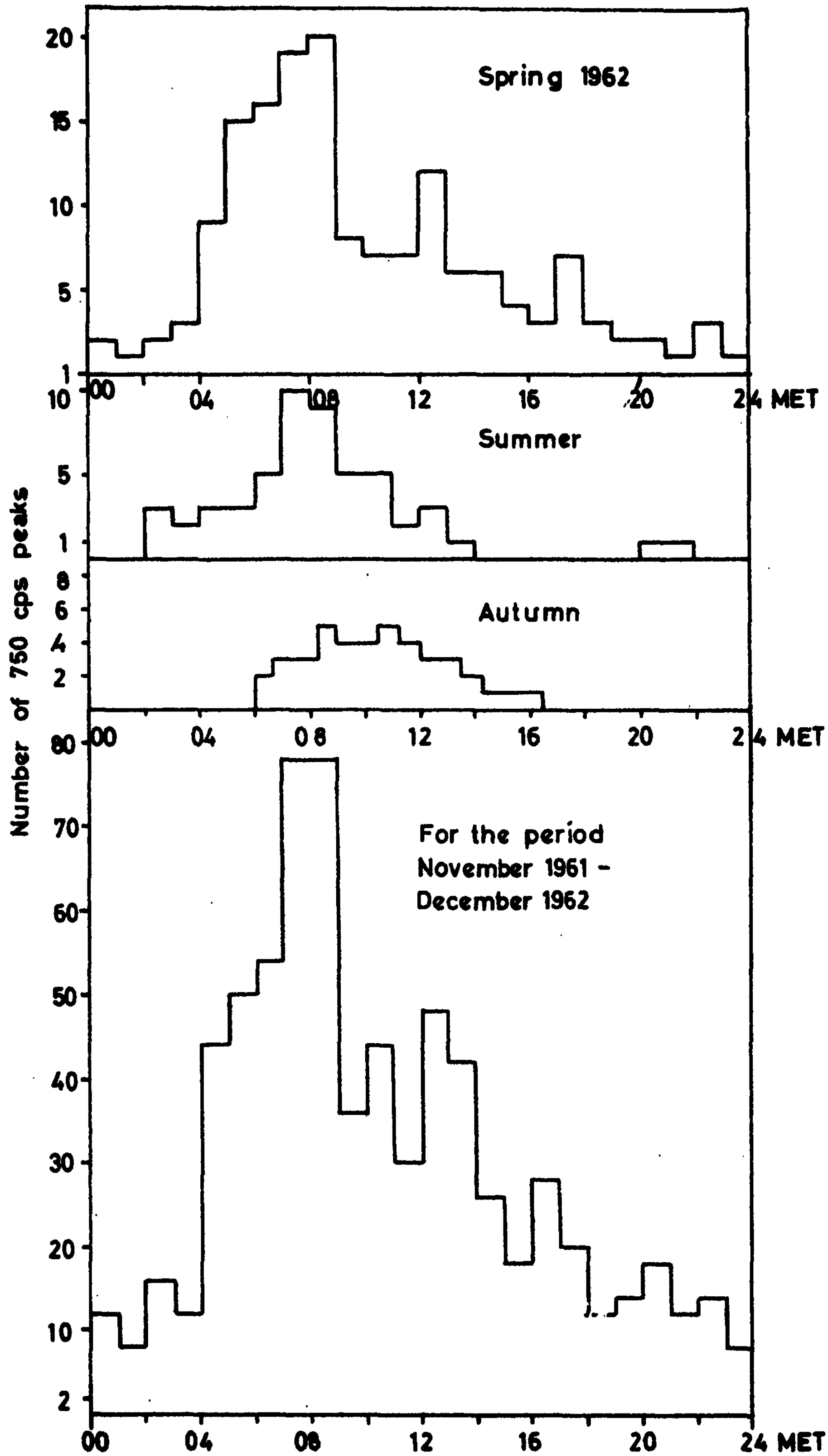
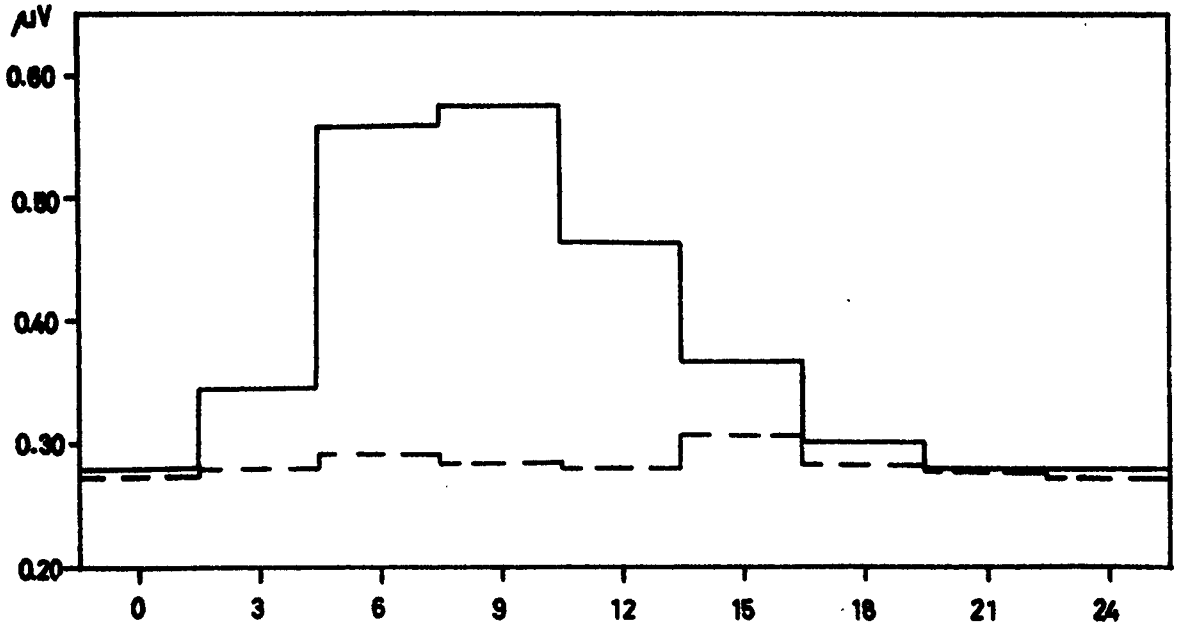


Fig. 7. Diurnal variation in the occurrence of the 700 cps radiation for the spring, summer, autumn, 1962 and for the recording period November, 1961 to December, 1962.



Number of 750 cps peaks

3	11	31	22	21	14	6	2	3

Total number of sweeps

80	80	80	48	58	80	80	80	80

Fig. 8.

Diurnal variation of the 700 cps radiation, compared with the 1000 cps level where all sweeps with 700 cps have been excluded (Paksuniemi)

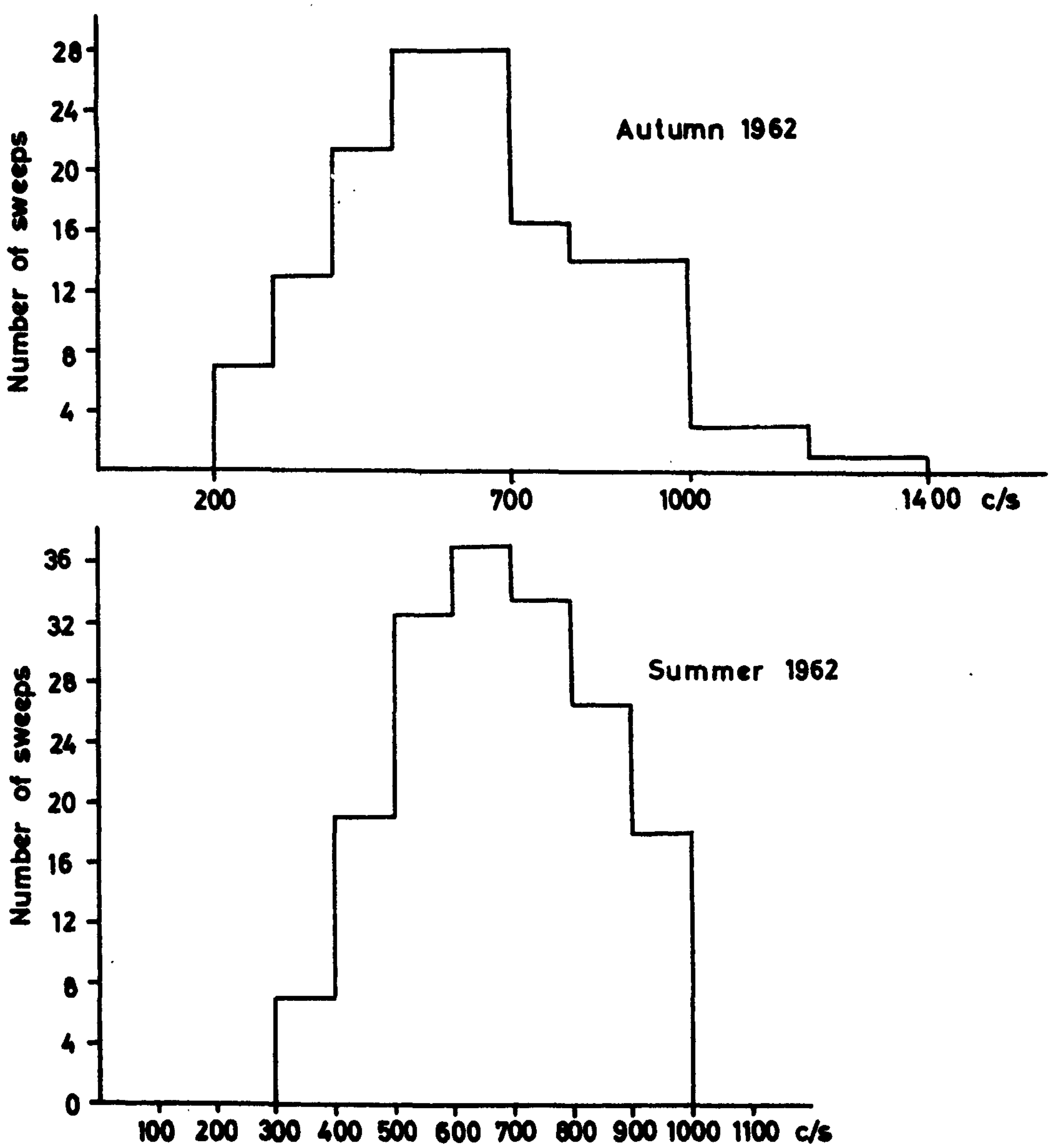


Fig. 9.

The average band widths of the 700 cps radiation, plotted on a linear frequency scale, for the summer and autumn period in 1962

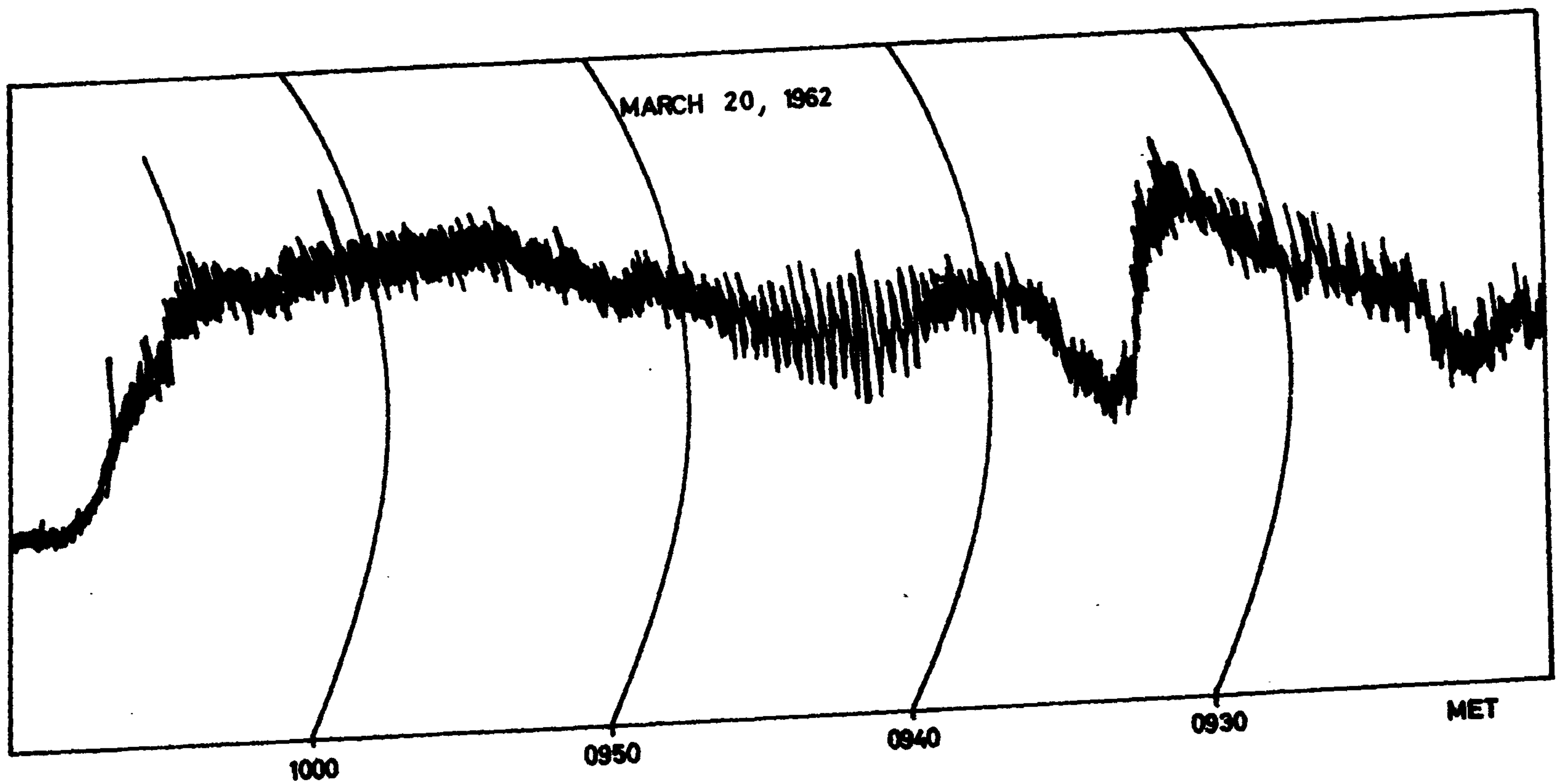


Fig. 10.
A fixed frequency record of the 700 cps radiation.
The bandwidth is 40 cps (Paksuniemi)

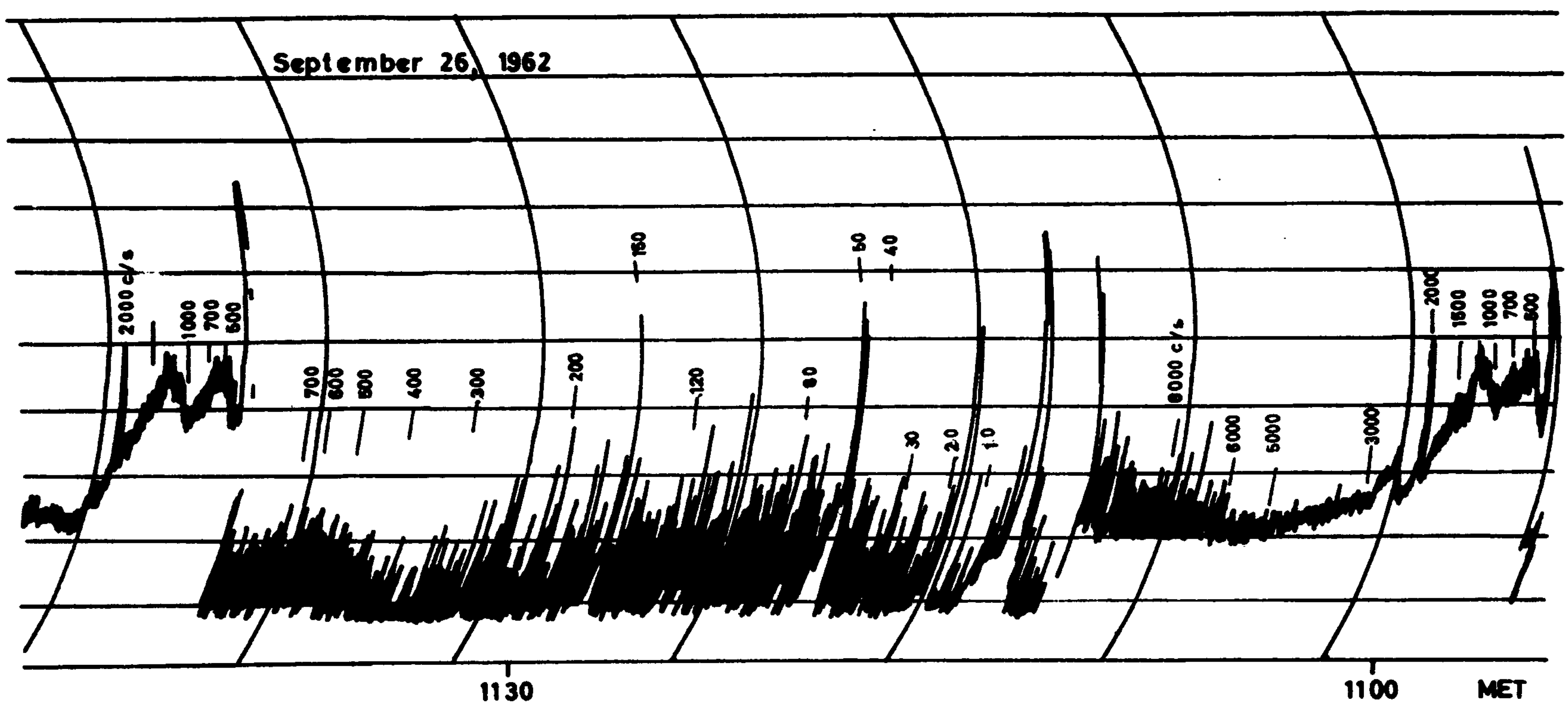


Fig. 11.

An example of a sweep showing the double emission peaks between 400 and 1500 cps

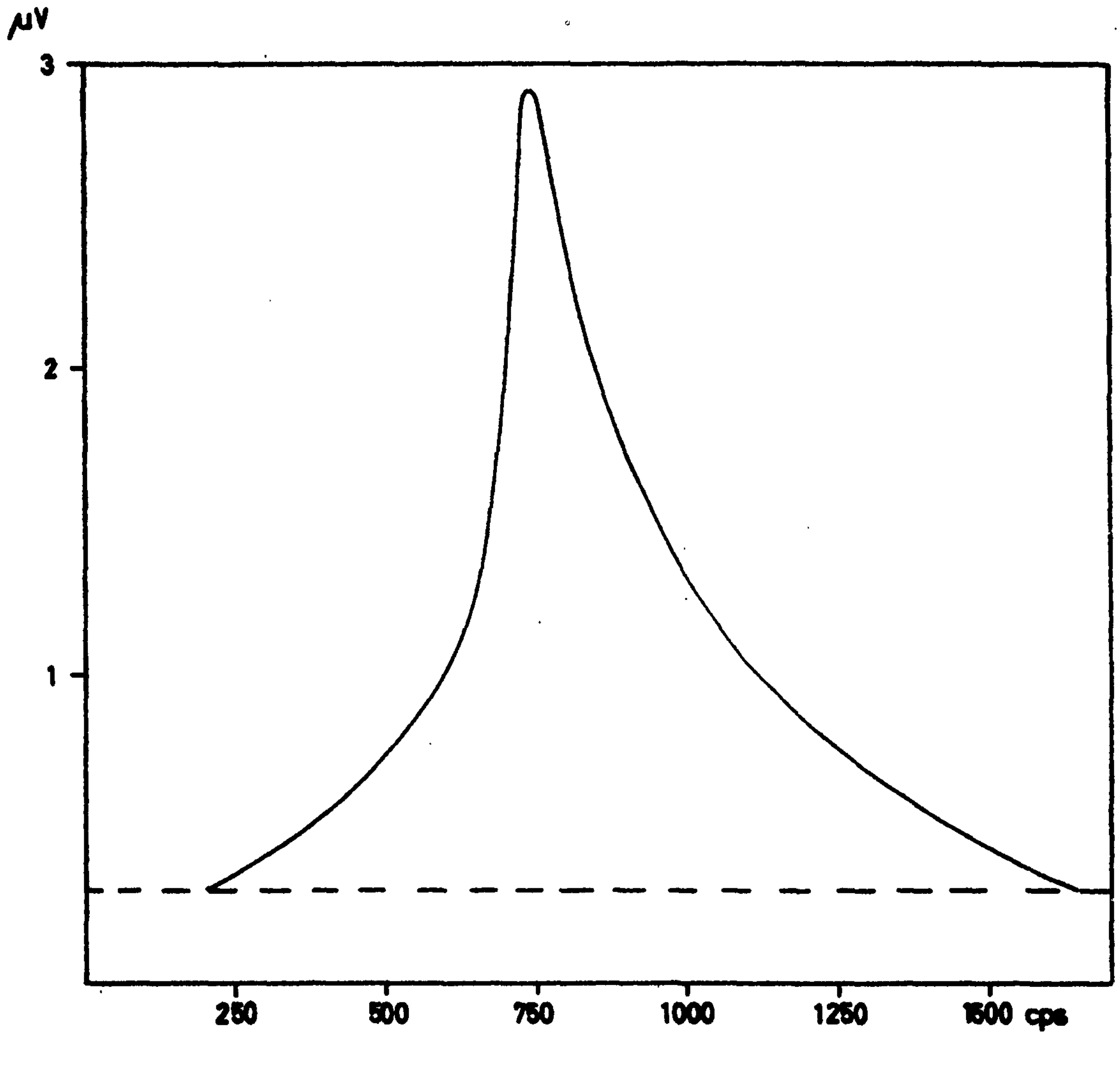


Fig. 12 a.

A 750 cps radiation band plotted on a linear frequency and amplitude scale. The line at the bottom indicates the normal noise level (Paksuniemi).

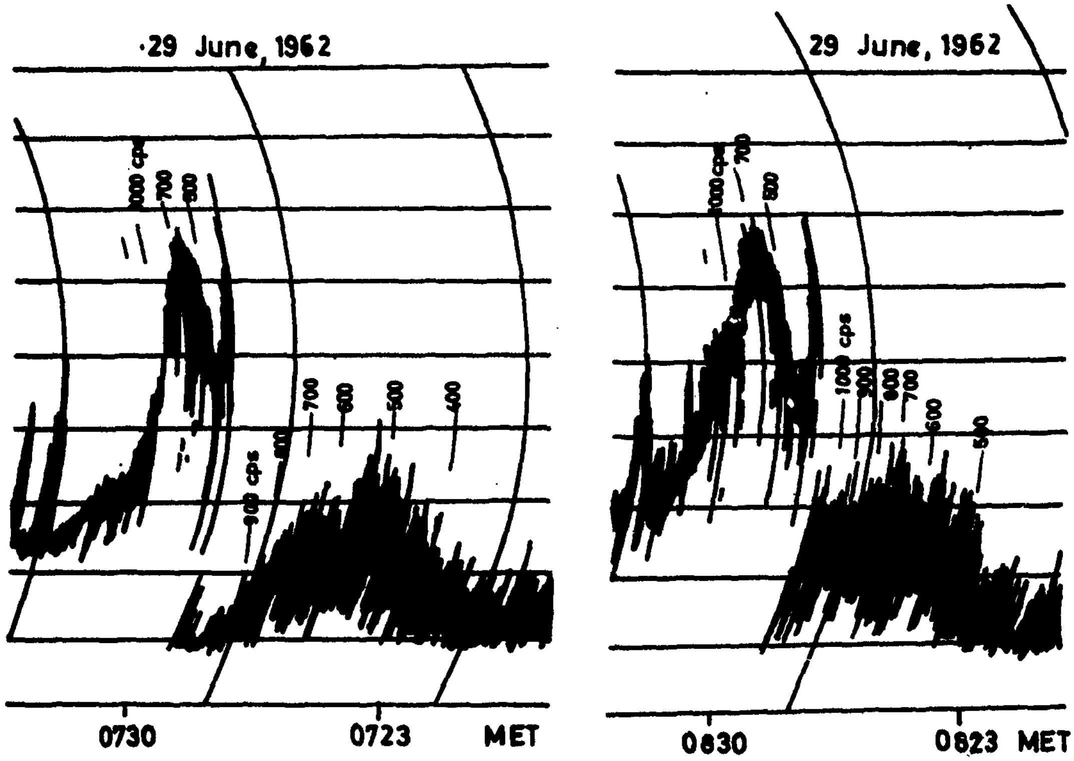
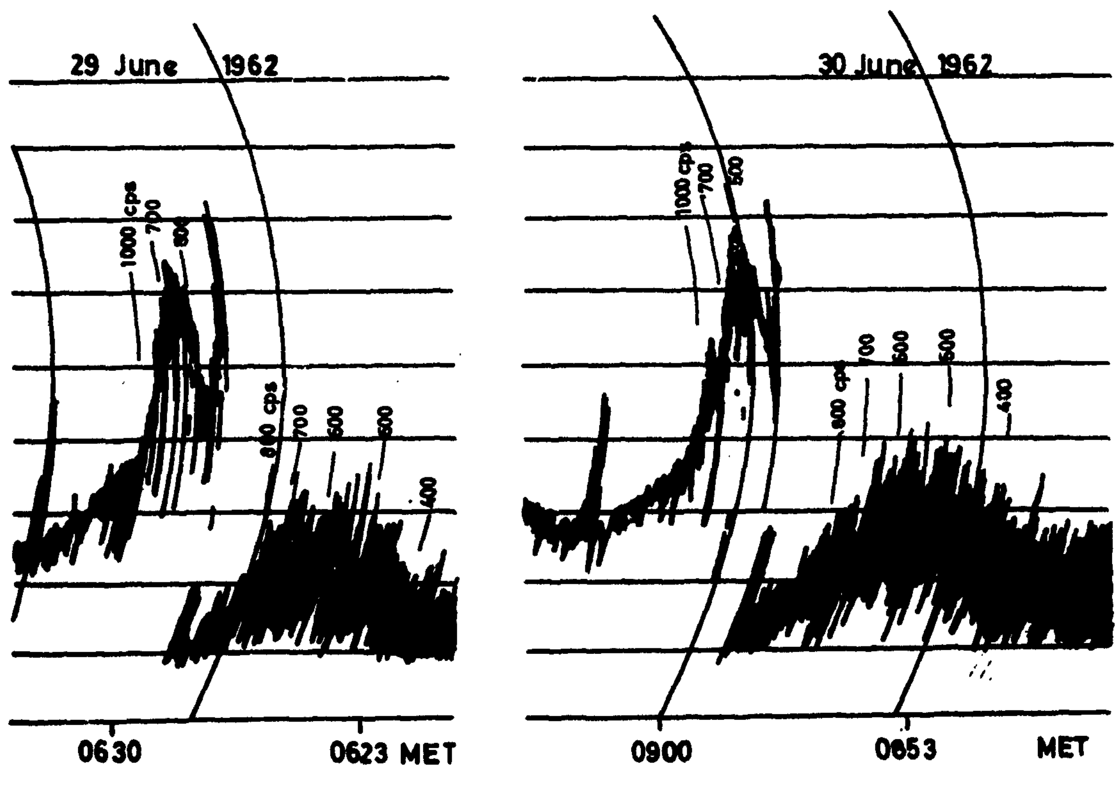


Fig. 12 b. Some examples of sweeps showing 700 cps emission in both the lower- and higher frequency range.



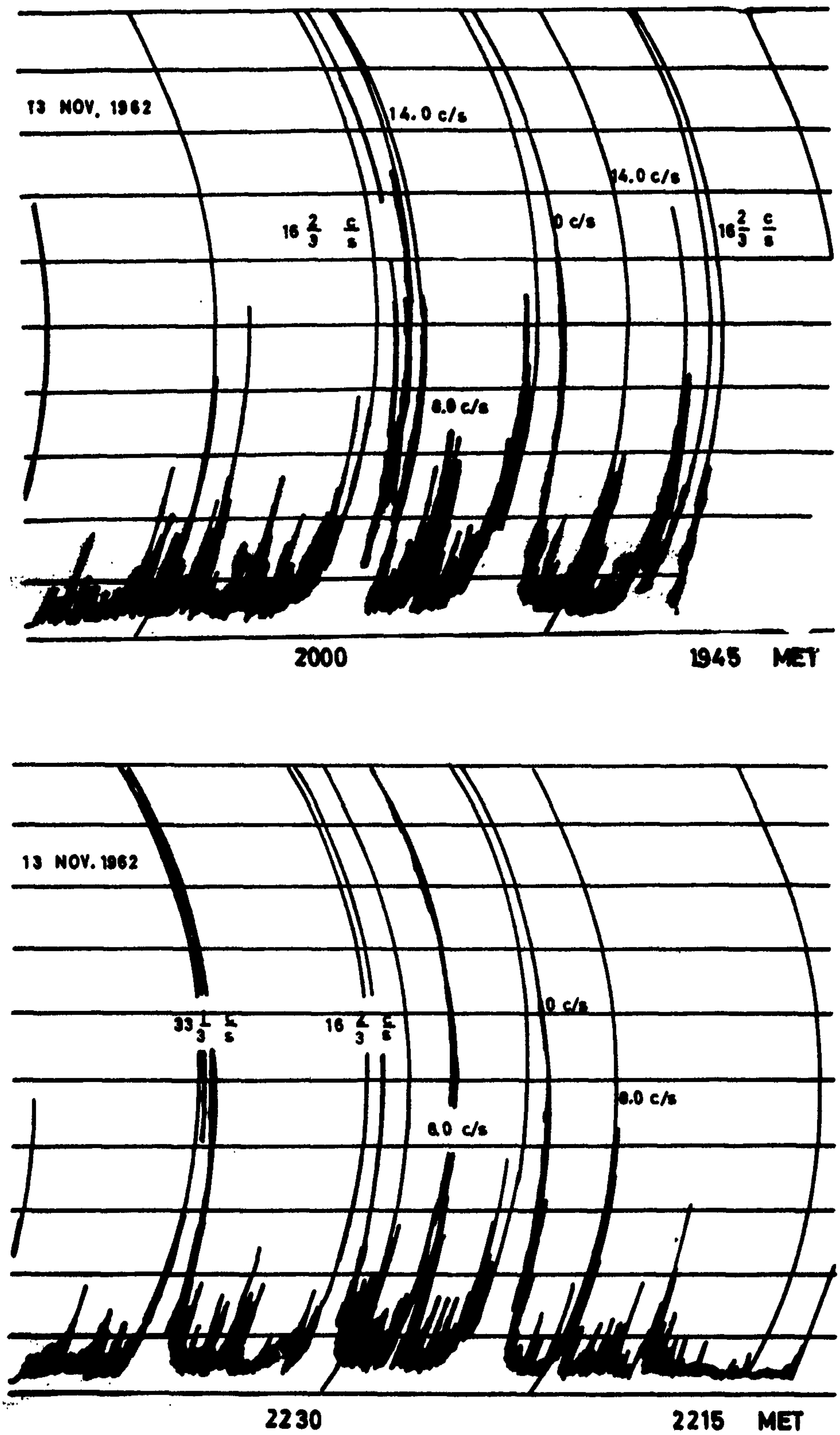
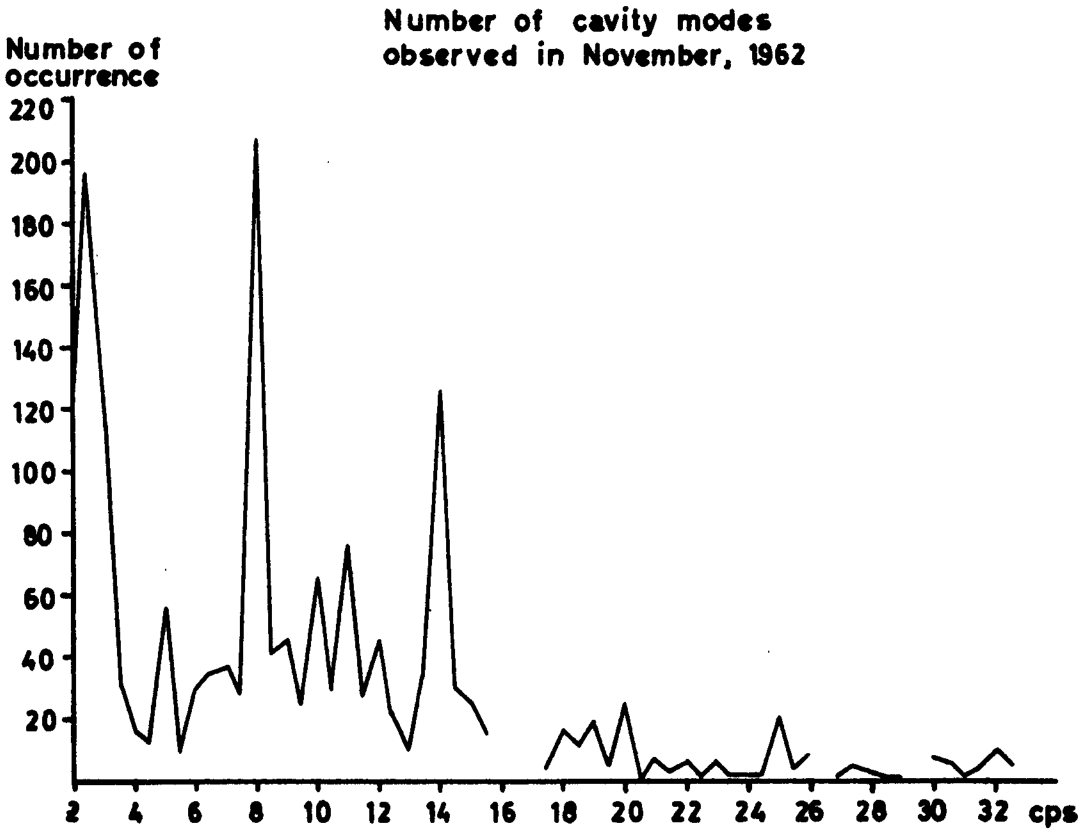


Fig. 13. Two examples of recordings showing the cavity modes in the range 2-40 cps



Number of cavity modes
observed in November, 1962
Number of
occurrence
220
200
180
160
140
120
100
80
60
40
20
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
cps

Fig. 14

Monitoring Agency Document No.
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by Alv Egeland, Sven Olsen and Georg Gustafsson
25 March 1963
KIRUNA GEOPHYSICAL OBSERVATORY, KIRUNA C, Sweden

Abstract: Fluctuations in the audio- and subaudio-frequency range have been extensively studied in recent years at Kiruna Geophysical Observatory (geomagnetic latitude 65.3°N). At this stage the experimental results can be summarised as follows. The experimental results are summarised under the headings of I) band emissions at gyro frequencies, II) diurnal variation of the background noise between 10 cps and 10.000 cps as a function of frequencies and time, and III) earth-ionosphere cavity resonances between 2 and 40 cps.

USAF, European Office, OAR, Brussels, Belgium

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